

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed and, completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information including suggestions for reducing this burden to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302 and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503</small>				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 6, 1999		3. REPORT TYPE AND DATES COVERED Technical Report
4. TITLE AND SUBTITLE Syntheses of Diaza-18-Crown-6 Ligands Containing Two Units Each of 4-Hydroxyazobenzene, Benzimidazole, Uracil, Anthraquinone, or Ferrocene Groups			5. FUNDING NUMBERS  N00014-98-1-0485 98PR05020-00	
6. AUTHOR(S) Ning Su, Jerald S. Bradshaw, Xian X. Zhang, Paul B. Savage, Krzysztof E. Krakowiak, and Reed M. Izatt				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Department of Chemistry and Biochemistry Brigham Young University Provo, UT 84602			8. PERFORMING ORGANIZATION REPORT NUMBER  Technical Report No 8	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Dr. Kelvin Higa (Program Director) Office of Naval Research 800 No. Quincy Street Arlington, VA 22217-5000			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT  Approved for public release; distribution unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)  Six diaza-18-crown-6 ligands each containing two aromatic side arms with responsive functions were prepared. Diaza-18-crown-6 containing two 4-hydroxyazobenzene or two 4-hydroxy-4'-(dimethylamino)-azobenzene (3 or 4) substituents were prepared <i>via</i> a one-pot Mannich reaction. Diaza-18-crown-6 containing two benzimidazole (5), two uracil (6) or two 9,10-anthraquinone (7) substituents were prepared by treating the diazacrown with the appropriate chloromethyl-containing compound. Reductive amination using sodium triacetoxymethylborohydride, diaza-18-crown-6 and ferrocenecarboxaldehyde was used to prepare bisferrocene-substituted diaza-18-crown-6 (8). Interactions of compounds 3, 5, and 6 with Na <sup>+</sup> , K <sup>+</sup> , Ba <sup>2+</sup> , Ag <sup>+</sup> , and Cu <sup>2+</sup> were evaluated by a calorimetric titration technique at 25° in methanol. All three ligands form more stable complexes with Ag <sup>+</sup> and Cu <sup>2+</sup> (5 forms a precipitate with Ag <sup>+</sup> ) than with Na <sup>+</sup> and K <sup>+</sup> . Ligand 5 also forms a highly stable complex with Ba <sup>2+</sup> .				
14. SUBJECT TERMS			15. NUMBER OF PAGES	
			16. PRICE CODE NA	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT Unlimited	

**OFFICE OF NAVAL RESEARCH**

Grant N00014-98-1-0485

Technical Report No. 8

**Syntheses of Diaza-18-Crown-6 Ligands Containing Two Units  
Each of 4-Hydroxyazobenzene, Benzimidazole, Uracil,  
Anthraquinone, or Ferrocene Groups**

by

Ning Su, Jerald S. Bradshaw, Xian X. Zhang, Paul B. Savage,  
Krzysztof E. Krakowiak, and Reed M. Izatt

Department of Chemistry and Biochemistry,  
Brigham Young University, Provo, UT 84602

April 6, 1999

Reproduction in whole or in part is permitted for  
any purpose of the University Government

This document has been approved for public release  
and sale; its distribution is unlimited

19990412 046

Syntheses of Diaza-18-Crown-6 Ligands Containing Two Units Each of 4-Hydroxyazobenzene, Benzimidazole, Uracil, Anthraquinone, or Ferrocene Groups

Ning Su, Jerald S. Bradshaw, Xian X. Zhang, Paul B. Savage,

Krzysztof E. Krakowiak, and Reed M. Izatt

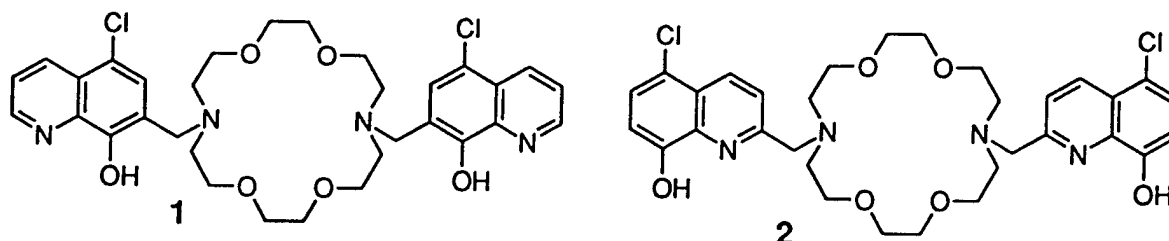
Department of Chemistry and Biochemistry

Brigham Young University, Provo, UT 84602

## Introduction.

We are interested in developing ion-selective chemosensors to monitor metal ion concentrations in a variety of aqueous solutions. Chemosensors are small molecules that bind selectively the desired analyte with measurable concomitant changes in the physical properties of the system. Chemosensors have been studied in which complexation has been shown by changes in fluorescence [1,2], uv-vis absorption spectra [3,4] or redox potentials [5]. In an effort to develop new selective chemosensors for metal ions, we have prepared macrocycles appended with chelating fluorophores, chromophores or ferrocene units. The macrocyclic portions of the new compounds are expected to provide ion-selective binding while the appended groups offer measurable changes in photophysical or redox properties indicating ion complexation.

For example, 8-hydroxyquinoline-containing ligand **1** (Figure 1), with the 8-hydroxyquinoline attached through its position 7, is selective for  $Mg^{2+}$  over other alkali and alkaline earth cations [6]. Ligand **1** can serve as an effective chemosensor for  $Mg^{2+}$  as it has a very strong luminescence band at 540 nm even in the presence of higher concentrations of other alkali and alkaline earth cations [7]. Ligand **2**, on the other hand, with the 8-hydroxyquinoline attached through its position 2 forms only a weak complex with  $Mg^{2+}$  but it exhibits remarkable selectivity for  $K^+$  and  $Ba^{2+}$  over other metal ions. Indeed, **2** formed a pseudocryptand when complexed with  $Ba^{2+}$  as shown by the  $^1H$  nmr spectrum and an X-ray crystal structure [6].

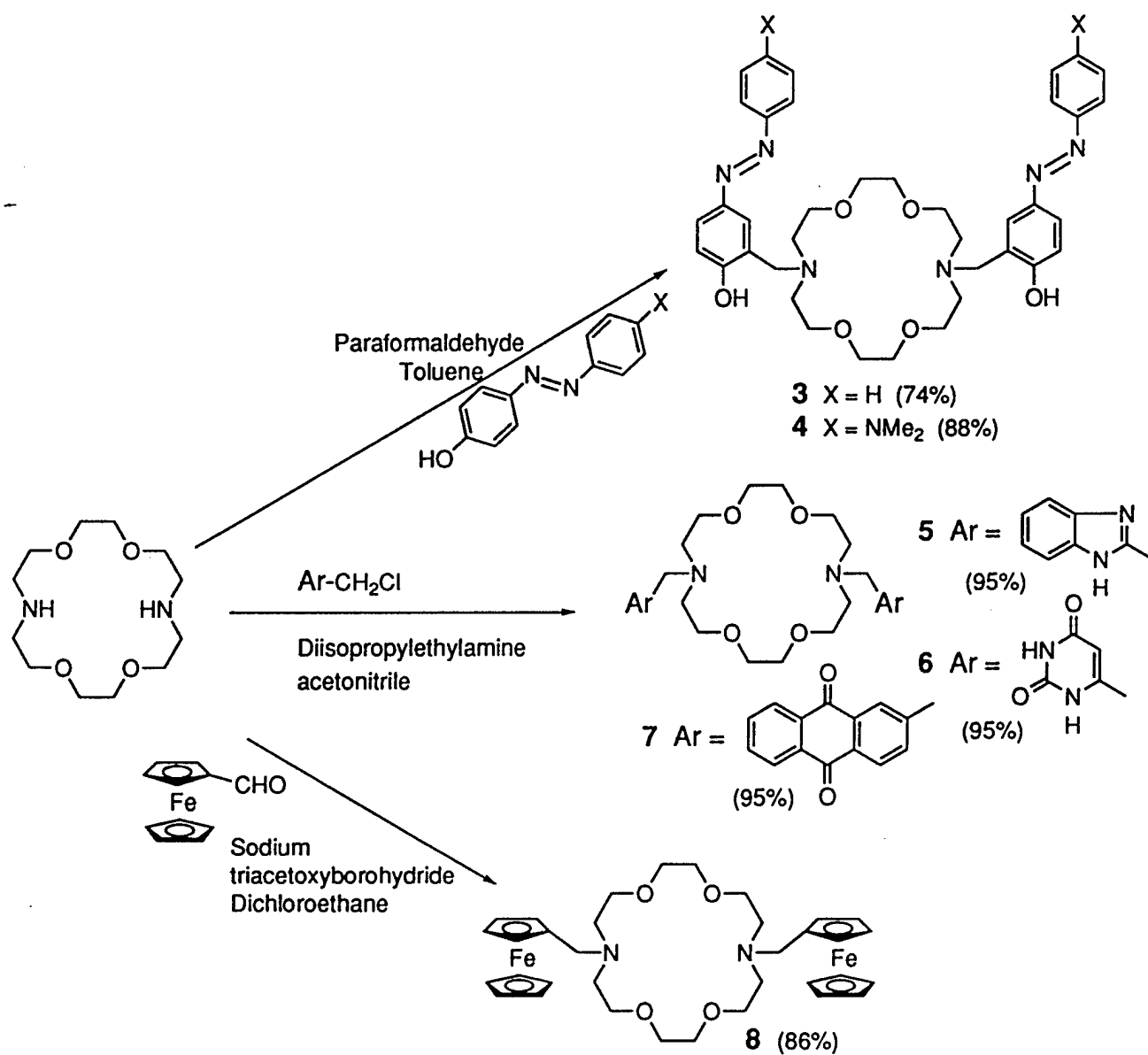


The azacrown ethers containing various aromatic substituents are generally prepared by treating the azacrown with the halomethyl-substituted aromatic compound. The Mannich reaction has also been used to attach various phenolic compounds to the azacrown ethers [6b, 8]. Aromatic substituents have also been attached to azacrown ethers by reductive amination using a suitable aromatic aldehyde [9].

In this report, we describe the syntheses of diaza-18-crown-6 ligands containing two units each of 4-hydroxyazobenzene (**3** and **4**), benzimidazole (**5**), uracil (**6**), 9,10-anthraquinone (**7**) or ferrocene (**8**) groups (Scheme 1). Ligands **3** and **4** were prepared by the Mannich reaction, **5-7** by treating the diazacrown with the appropriate chloromethyl-containing compound and **8** by reductive amination using ferrocenecarboxaldehyde.

## Results and Discussion.

Most chromoionophores designed to be selective for metal ions are of the proton-ionizable type [10]. Interaction of the proton-ionizable group with a complexed metal ion is reflected by changes in the optical properties of the chromoionophore. In addition, the



Scheme 1. Synthesis of Diaza-18-crown-6 Containing Two Side Arms

deprotonated form can form stronger complexes with metal ions than the neutral form. Ligands 3 and 4 (Scheme 1) combine the complexation properties of proton-ionizable macrocyclic ligands with the signaling properties of the azobenzene chromoionophore. These types of compounds have been prepared by first attaching phenol derivatives onto the azacrown followed by reaction with the appropriate diazonium salt [11]. Performing a coupling reaction on two phenol groups attached to a diazacrown ether would be much less efficient than attaching an already formed azo compound. For this reason, we attached 4-phenylazophenol and 4-hydroxy-4'-(dimethylamino)azobenzene to diaza-18-crown-6 by means of a one-pot Mannich reaction [12] to give 3 and 4, respectively (Scheme 1).

Benzimidazole-containing ligand 5 was prepared by treating diaza-18-crown-6 with 2-(chloromethyl)benzimidazole in acetonitrile in the presence of *N,N*-diisopropylethylamine. Uracil-containing ligand 6 was prepared by treating diaza-18-crown-6 with 6-(chloromethyl)uracil. Anthraquinone-containing ligand 7 was synthesized by treating diaza-18-crown-6 with 2-(chloromethyl)-9,10-anthraquinone in the presence of *N,N*-diisopropylethylamine in acetonitrile as shown in Scheme 1. Ligand 8 [17], containing two ferrocene units, on the other hand, was synthesized by an efficient reductive amination process [9]. Ferrocenecarboxaldehyde, diaza-18-crown-6, and sodium triacetoxymethylborohydride were stirred together for 12 hours to give 8 in an 86% yield. Pure 8 was isolated by ultrasonication of the crude product in methanol followed by filtration. Separation by chromatography was not needed.

Interactions of ligands 3, 5, and 6 with  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ba}^{2+}$ ,  $\text{Ag}^+$ , and  $\text{Cu}^{2+}$  have been evaluated by a calorimetric titration technique [13] at 25° in absolute methanol solution. The values of equilibrium constants ( $\log K$ ) and enthalpy ( $\Delta H$ ) and entropy changes ( $T\Delta S$ ) for these interactions are listed in Table 1. Because of the very low solubility of 4 and 7 in methanol, the thermodynamic quantities involving these two compounds were not evaluated. Ligand 6 has two uracil sidearms and shows weaker interaction with all metal ions studied than ligands 3 and 5. All three ligands form more stable complexes with  $\text{Ag}^+$  and  $\text{Cu}^{2+}$  (5 and  $\text{Ag}^+$  form a precipitate) than with  $\text{Na}^+$  and  $\text{K}^+$ .

Hydroxyazobenzene-containing ligand 3 shows a high selectivity for  $\text{Ag}^+$  ( $\log K = 6.60$ ) over  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{Ba}^{2+}$  and benzimidazole-containing ligand 5 shows high selectivities for  $\text{Ba}^{2+}$  ( $\log K > 5.5$ ) and  $\text{Cu}^{2+}$  ( $\log K > 5.5$ ) over  $\text{Na}^+$  ( $\log K = 3.25$ ) and  $\text{K}^+$  ( $\log K = 3.67$ ). The  $^1\text{H}$  nmr spectrum of the 5- $\text{Ba}^{2+}$  complex suggests that the two benzimidazole rings and the macrocyclic ring are involved in complexation since nmr signals for one benzene hydrogen atom and various ring hydrogen atoms are shifted down field. Although the interactions of uracil-containing 6 with the metal ions are weaker than those of 3 and 5, it still shows good selectivity for  $\text{Ag}^+$  and  $\text{Cu}^{2+}$  over  $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{Ba}^{2+}$ .

As compared with 8-hydroxyquinoline-containing ligand 2 [6], 5 likewise forms a highly stable complex with  $\text{Ba}^{2+}$  but the stability of the 5- $\text{Cu}^{2+}$  complex is higher than that of the 2- $\text{Cu}^{2+}$  one. Stability of  $\text{Cu}^{2+}$  complexes with 3 and 6 are much lower than that with 8-hydroxyquinoline-containing ligand 1 [6]. The  $\text{K}^+/\text{Na}^+$  selectivity demonstrated by 3 and 5 is close to that by 1 but much less than that by 2.

**Table 1.** Log  $K$ ,  $\Delta H$  (kJ/mol), and  $T\Delta S$  (kJ/mol) Values for Interactions of Macrocyclic Ligands

with Metal Ions in Methanol Solution at 25.0°

ligand	cation	log $K$	$\Delta H$	$T\Delta S$
1 [a]	Na <sup>+</sup>	2.89 ± 0.05	-14.1 ± 0.8	2.4
	K <sup>+</sup>	3.39 ± 0.03	-24.4 ± 0.7	-5.0
	Ba <sup>2+</sup>	3.60 ± 0.05	-11.6 ± 0.5	8.9
	Cu <sup>2+</sup>	10.1 ± 0.1	-92.5 ± 0.6	-34.9
2 [a]	Na <sup>+</sup>	3.74 ± 0.01	-26.4 ± 0.3	-5.1
	K <sup>+</sup>	6.61 ± 0.03	-58.1 ± 0.1	-20.4
	Ba <sup>2+</sup>	12.2 ± 0.4	-76.1 ± 0.7	-6.5
	Cu <sup>2+</sup>	4.7 ± 0.2	-116 ± 4	-89
3	Na <sup>+</sup>	2.44 ± 0.02	-16.3 ± 0.5	-2.4
	K <sup>+</sup>	2.87 ± 0.06	-27.8 ± 0.8	-11.4
	Ba <sup>2+</sup>	4.24 ± 0.07	-32.6 ± 0.8	-8.4
	Ag <sup>+</sup>	6.60 ± 0.05 [c]	-62.3 ± 0.6 [c]	-24.6
	Cu <sup>2+</sup>	5.27 ± 0.08	-66.8 ± 0.8	-36.7
5	Na <sup>+</sup>	3.25 ± 0.03	-12.0 ± 0.7	6.55
	K <sup>+</sup>	3.67 ± 0.02	-33.8 ± 0.6	-12.9
	Ba <sup>2+</sup>	> 5.5	-26.3 ± 0.4	>5.1
	Ag <sup>+</sup>	(Brown precipitate)		
	Cu <sup>2+</sup>	> 5.5	-56.0 ± 0.7	>-24.6
6	Na <sup>+</sup>	[b]		
	K <sup>+</sup>	[b]		
	Ba <sup>2+</sup>	[b]		
	Ag <sup>+</sup>	4.96 ± 0.01	-51.8 ± 0.3	-23.5
	Cu <sup>2+</sup>	4.18 ± 0.06	-55.0 ± 0.8	-31.1

[a] Reference 6b.

[b] No measurable heat other than heat of dilution indicating that  $\Delta H$  or/and log  $K$  is small.

[c] Quantities were determined by competitive calorimetric titration.

## EXPERIMENTAL

The  $^1\text{H}$  nmr spectra (300 MHz) and  $^{13}\text{C}$  nmr spectra (75 MHz) were recorded in deuterochloroform or perdeutereodimethyl sulfoxide. FAB ionization was used to record the high resolution mass spectra. Solvents and starting materials were purchased from commercial sources where available.

General Procedure A for the Syntheses of Compounds 3 and 4 Using the One-pot Mannich Reaction [12].

An anhydrous toluene solution (180 ml) of 4,13-diaza-18-crown-6 (1.0 g, 3.8 mmole), paraformaldehyde (280 mg, 9.3 mmole), and the appropriate phenol (9.1 mmole) was refluxed for 20 hours. The solvent was evaporated under reduced pressure and a small amount of methanol was added. The mixture was ultrasonicated for 20 to 30 minutes and the resulting solid was filtered and dried.

General Procedure B for the Synthesis of Compounds 5-7 [14].

4,13-Diaza-18-crown-6 (1.0 g, 3.8 mmole), *N,N*-diisopropylethylamine (2.7 ml, 15.3 mmole), and the appropriate compounds containing chloromethyl groups (8.4 mmole) in 200 ml of acetonitrile were refluxed for 12 hours and cooled to room temperature. After standing overnight, the precipitate was filtered and dried. The product was further purified by ultrasonication in a small amount of methanol followed by filtration and drying.

7,16-Bis(2-hydroxy-5-(phenylazo)benzyl)-1,4,10,13-tetraoxa-7,16-diazacyclooctadecane (3).

Compound 3 was prepared by general procedure A from 4-phenylazophenol to give a light yellow solid; mp 111-113°; yield 74%;  $^1\text{H}$  nmr  $\delta$ : 2.92 (t,  $J$  = 5.2 Hz, 8H), 3.63 (s, 8H), 3.70 (t,  $J$  = 5.2 Hz, 8H), 3.93 (s, 4H), 6.94 (d,  $J$  = 8.5 Hz, 2H), 7.47 (m, 6H), 7.65 (d,  $J$  = 2.0 Hz, 2H), 7.84 (m, 6H);  $^{13}\text{C}$  nmr  $\delta$ : 53.98, 58.64, 69.11, 71.00, 117.05, 122.61, 122.97, 123.10, 125.45, 129.21, 130.30, 145.98, 153.03, 161.74; hrms calcd for  $\text{C}_{38}\text{H}_{46}\text{N}_6\text{O}_6$  ( $\text{M}+\text{Na}$ ) $^+$  705.3357, found 705.3386.

*Anal.* Calcd for  $\text{C}_{38}\text{H}_{46}\text{N}_6\text{O}_6$ : C, 66.84; H, 6.79. Found: C, 67.09; H, 6.75.

7,16-Bis(2-hydroxy-5-(4'-dimethylaminophenylazo)benzyl)-1,4,10,13-tetraoxa-7,16-diazacyclooctadecane (4).

Compound 4 was prepared by general procedure A from 4-hydroxy-4'-(dimethylamino)azobenzene to give a yellow solid; mp 185-186°; yield 88%;  $^1\text{H}$  nmr  $\delta$ : 2.90 (t,  $J$  = 5.2 Hz, 8H), 3.06 (s, 12 H), 3.63 (s, 8H), 3.56 (d,  $J$  = 5.2 Hz, 8H), 3.91 (s, 4H), 6.75 (d,  $J$  = 9.0 Hz, 4H), 6.91 (d,  $J$  = 8.6 Hz, 2H), 7.56 (d,  $J$  = 2.2 Hz, 2H), 7.74 (dd,  $J$  = 2.2, 8.5 Hz, 2H), 7.81 (d,  $J$  = 9.0 Hz, 4H);  $^{13}\text{C}$  nmr  $\delta$ : 40.56, 53.96, 58.78, 69.19, 70.98, 111.83, 116.90, 122.27, 122.85, 124.47, 124.51, 143.94, 146.40, 152.07, 160.25; hrms calcd for  $\text{C}_{42}\text{H}_{56}\text{N}_8\text{O}_6$  ( $\text{M}+\text{Na}$ ) $^+$



791.4221; found: 791.4204.

*Anal.* Calcd for  $C_{42}H_{56}N_8O_6 \cdot 0.5H_2O$ : C, 64.84; H, 7.38. Found: C, 64.80; H, 7.26.

7,16-Bis(benzimidazol-2-ylmethyl)-1,4,10,13-tetraoxa-7,16-diazacyclooctadecane (5).

Compound 5 was prepared by general procedure B from 2-(chloromethyl)benzimidazole to give a light yellow solid; mp 213-215°; yield 95%;  $^1H$  nmr  $\delta$ : 2.82 (bs, 8H), 3.52 (m, 16H), 4.08 (s, 4H), 7.15 (s, 4H), 7.36 (s, 2H), 7.68 (s, 2H), 11.64 (s, 2H);  $^{13}C$  nmr  $\delta$ : 54.25, 56.43, 69.27, 70.47, 111.30, 119.00, 121.93, 122.03, 134.25, 143.75, 154.49; hrms calcd for  $C_{28}H_{38}N_6O_4$  ( $M+Na$ )<sup>+</sup> 545.2833, found 545.2860.

*Anal.* Calcd for  $C_{28}H_{38}N_6O_4$ : C, 64.35; H, 7.33. Found: C, 64.41; H, 7.22.

7,16-Bis(uracil-6-ylmethyl)-1,4,10,13-tetraoxa-7,16-diazacyclooctadecane (6).

Compound 6 was prepared by general procedure B from 6-(chloromethyl)uracil (dissolved in a small amount of dimethylformamide) to give a light yellow solid; mp 233-235°; yield 95%;  $^1H$  nmr  $\delta$ : 2.72 (m, 8H), 3.42 (s, 2H), 3.52 (m, 16H), 5.52 (s, 4H), 10.26 (s, 2H), 10.89 (s, 2H);  $^{13}C$  nmr  $\delta$ : 53.88, 54.76, 68.92, 69.69, 97.47, 151.38, 155.16, 164.22; hrms calcd for  $C_{22}H_{34}N_2O_6$  ( $M+H$ )<sup>+</sup> 511.2518, found 511.2520.

*Anal.* Calcd for  $C_{22}H_{34}N_2O_6$ : C, 51.76; H, 6.71. Found: C, 52.00; H, 6.66.

7,17-Bis(9,10-anthraquinon-2-ylmethyl)-1,4,10,13-tetraoxa-7,16-diazacyclooctadecane (7).

Compound 7 was prepared by general procedure B from 2-(chloromethyl)-9,10-anthraquinone to give a light yellow solid; mp 174-175°; yield 95%;  $^1H$  nmr  $\delta$ : 2.87 (t,  $J$  = 5.6 Hz, 8H), 3.64 (s, 8H), 3.68 (t,  $J$  = 5.6 Hz, 8H), 3.88 (s, 4H), 7.79 (m, 6H), 8.24 (m, 8H);  $^{13}C$  nmr  $\delta$ : 54.17, 59.58, 69.99, 70.86, 126.91, 127.08, 127.31, 132.26, 133.28, 133.50, 133.52, 133.89, 133.96, 134.29, 147.66, 182.92, 193.23; hrms calcd for  $C_{42}H_{42}N_2O_8$  ( $M+Na$ )<sup>+</sup> 725.2818, found 725.2839.

*Anal.* Calcd for  $C_{42}H_{42}N_2O_8$ : C, 71.78; H, 6.02. Found: C, 72.00; H, 6.42.

7,16-Bisferrocenylmethyl-1,4,10,13-tetraoxa-7,16-diazacyclooctadecane (8).

4,13-Diaza-18-crown-6 (1.0 g, 3.8 mmole) and ferrocenecarboxaldehyde (1.72 g, 8.02 mmole) were mixed in 1,2-dichloroethane (30 ml) and then treated with sodium triacetoxyborohydride (2.45 g, 11.5 mmole) [9]. The mixture was stirred at room temperature under a nitrogen atmosphere for 12 hours. The reaction was quenched by adding aqueous saturated sodium bicarbonate and the product was extracted with chloroform. The chloroform extract was dried and the solvent was evaporated. A small amount of methanol was added to the crude product and the mixture was ultrasonicated for 30 minutes. The deposit was filtered, washed with cold methanol, and dried to give pure compound 8, a dark yellow solid, in an 86% yield. The mp and NMR spectra data were identical with those reported [15].

Determination of Thermodynamic Quantities.

Values of  $\log K$ ,  $\Delta H$ , and  $T\Delta S$  were determined as described earlier [13] in absolute methanol solutions at  $25.0 \pm 0.1^\circ$  by titration calorimetry using a Tronac Model 450 calorimeter equipped with a 20-ml reaction vessel. The metal ion solutions were titrated into the macrocyclic ligand solutions and the titrations were carried out to a 2-fold excess of the metal ions. The titration experiments showed that all interactions studied had a 1:1 cation-ligand ratio. The methods used to process the calorimetric data and to calculate the  $\log K$  and  $\Delta H$  values have been described [16].

## REFERENCES

- [1a] A. W. Czarnik, *Acc. Chem. Res.*, **27**, 302 (1990); [b] L. Fabbrizzi, M. Licchelli, P. Pallavicini, A. Perotti, and D. Sacchi, *Angew. Chem. Int. Ed. Engl.*, **33**, 1975 (1994); [c] Q. Zhou and T. M. Swager, *J. Am. Chem. Soc.*, **117**, 7017 (1995); [d] D. M. Rudkevich, W. Verboom, E. Van Der Tol, C. J. Van Staveren, F. M. Kaspersen, J. W. Verhoeven, and D. N. Reinhoudt, *J. Chem. Soc., Perkin Trans. II*, 131 (1995); [e] D. Marquis, J.-P. Desvergne, and H. Bouas-Laurent, *J. Org. Chem.*, **60**, 7984 (1995); [f] H. Matsumoto and S. Shinkai, *Tetrahedron Lett.*, **37**, 77 (1996).
- [2a] A. P. de Silva, H. Q. N. Gunaratne, T. Gunnlaugsson, A. J. M. Huxley, C. P. McCoy, J. T. Rademacher, and T. E. Rice, *Chem. Rev.*, **97**, 1515 (1997); [b] *Fluorescent Chemosensors for Ion and Molecular Recognition*, A. W. Czarnik, ed., American Chemical Society, Washington, D. C. 1992.
- [3] Z. Marczenko, *Separation and Spectrophotometric Determination of Elements*; John Wiley & Sons: New York, 1986.
- [4a] E. Linder, M. Horvath, K. Toth, and E. Pungor, *Anal. Lett.*, **25**, 453 (1992); [b] R. A. Bartsch, E. Chapoteau, B. P. Czech, J. Krzykowski, A. Kumar, and T. W. Robinson, *J. Org. Chem.*, **59**, 616 (1994); [c] Y. Kobo, S. Maeda, M. Nakamura, and S. Tokita, *J. Chem. Soc.*, 1725 (1994); [d] T. W. Brockmann and J. M. Tour, *J. Am. Chem. Soc.*, **117**, 4437 (1995).
- [5] T. E. Edmonds, *Chemical Sensors*; Blackie: Glasgow and London, 1988.
- [6a] X. X. Zhang, A. V. Bordunov, J. S. Bradshaw, N. K. Dalley, X. Kou, and R. M. Izatt, *J. Am. Chem. Soc.*, **117**, 11507 (1995); [b] A. V. Bordunov, J. S. Bradshaw, X. X. Zhang, N. K. Dalley, X. Kou, and R. M. Izatt, *Inorg. Chem.*, **35**, 7229 (1996); [c] J. S. Bradshaw and R. M. Izatt, *Acc. Chem. Res.*, **30**, 338 (1997).
- [7] L. Prodi, F. Bolletta, M. Montali, N. Zaccheroni, P. B. Savage, J. S. Bradshaw, and R. M. Izatt, *Tetrahedron Lett.*, **39**, 5451 (1998).
- [8] A. V. Bordunov, J. S. Bradshaw, V. N. Pastushok, and R. M. Izatt, *SynLett*, 933 (1996).
- [9a] A. F. Abdel-Magid, K. G. Carson, B. D. Harris, C. A. Maryanoff, and R. D. Shah, *J. Org. Chem.*, **61**, 3849 (1996); [b] R. F. Borch and A. I. Hassid, *J. Org. Chem.*, **37**, 1673 (1972); [c] F. J. McEvoy and G. R. Allen, *J. Med. Chem.*, **17**, 281 (1974).
- [10a] Y. Katayama, R. Fukuda, and M. Takagi, *Anal. Chim. Acta.*, **185**, 295 (1986); [b] Y. Katayama, R. Fukuda, K. Hiwatari, and M. Takagi, *Rep. Asahi Glass Found. Ind. Technol.*, **48**, 193 (1986).
- [11] S. Akabori, Y. Miura, N. Yotsumoto, K. Uchida, M. Kitano, and Y. Habata, *J. Chem. Soc., Perkin Trans. I*, 2589 (1995).
- [12] K.-W. Chi, H.-C. Wei, T. Kottke, and R. J. Lagow, *J. Org. Chem.*, **61**, 5684 (1996).

- [13a] J. L. Oscarson and R. M. Izatt, In *Physical Methods of Chemistry* Vol. VI: Determination of Thermodynamic Properties, B. W. Rossiter and R. C. Baetzold, eds.; John Wiley & Sons: New York, 1992; Chapter 7. [b] R. M. Izatt, X. X. Zhang, H. Y. An, C. Y. Zhu, and J. S. Bradshaw, *Inorg. Chem.*, **33**, 1007 (1994).
- [14a] M. Shiga, H. Nishida, H. Nakamura, M. Takagi, and K. Ueno, *Bunseki Kagaku*, **32**, E293 (1993); [b] A. V. Bordunov, P. C. Hellier, J. S. Bradshaw, N. K. Dalley, X.-L. Kou, X. X. Zhang, and R. M. Izatt, *J. Org. Chem.*, **60**, 6097 (1995).
- [15a] J. C. Medina, T. T. Goodnow, M. Rojas, J. L. Atwood, B. C. Lynn, A. E. Kaifer, and G. W. Gokel, *J. Am. Chem. Soc.*, **114**, 10583 (1992). [b] P. D. Beer, J. E. Nàtìon, S. L. McWhinnie, M. E. Harman, M. B. Hursthouse, M. I. Ogden, and A. H. White, *J. Chem. Soc., Dalton Trans.*, 2485 (1991).
- [16] D. J. Eatough, J. J. Christensen, and R. M. Izatt, *Thermochim. Acta*, **3**, 219 and 233 (1972).